Adaptive Range Multi-Objective Genetic Algorithms for Aerodynamic Design Problems(空力設計問題における領域適応型多目的遺伝的アルゴリズム)

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論文内容要旨

Chapter 1 Introduction

With a significant advancement in Computational Fluid Dynamics (CFD) techniques, aerodynamic optimisation has been gradually adapted these days. The advancement in CFD techniques, whose aim is to develop numerical algorithms to solve the fluid dynamics equations accurately and efficiently, has been achieved within the last 30 years, with the aid of a rapid progress in computer performances. The progresses enable high-fidelity CFD (Euler/Navier-Stokes solver) to be adopted in aerodynamic design system. Therefore, many aerodynamic design optimisations coupled with high-fidelity CFD have been studied to obtain more suitable designs based on various optimisation algorithms.

It is common that many real-world design problems have multiple design objectives that may have conflicting requirements. One of the aim of multi-objective optimisation is to determine trade-offs among multiple design requirements, which are represented by non-dominated solutions. To select the best solution from a set of non-dominated solutions, it would be better to sample many non-dominated solutions. Ideally, Pareto solutions, which mean global non-dominated solutions that form global trade-offs, should be obtained. It is also useful to analyse trade-offs, because it will help to understand the design space and provide the information for further improvement.

Multi-Objective Evolutionary Algorithms (MOEAs) have gained popularity because of their ability to find global trade-offs and the usefulness of the trade-off information. However, as it is well-known, MOEAs require a large number of evaluations. This could be a major inhibitor in applying MOEAs to aerodynamic optimisations using time-consuming high-fidelity CFD. Therefore, MOEAs will become more practical methods to solve multi-objective aerodynamic optimisation problems if more efficient algorithm can be developed.

The objective of the present thesis is to develop efficient MOEAs to conduct practical multi-objective aerodynamic optimizations. Such MOEAs must obtain high-quality trade-offs with a small number of evaluations to make it practical for aerodynamic optimisation. In this thesis, Adaptive Range Multi-Objective Genetic Algorithms (ARMOGAs) are developed to identify trade-offs efficiently. In order to evaluate search performance of ARMOGAs, several analytical test problems are compared with other optimisers. In addition, ARMOGAs are also applied to conduct multi-objective aerodynamic optimisations. One of the targets is the Low Pressure Compression (LPC) system in a modern gas-turbine engine, which is being developed in the aerospace industry. Another is the Supersonic Transport (SST) to realise its requirements in terms of economical flight and less environmental effect.

Chapter 2 Adaptive Range Multi-Objective Genetic Algorithms

Many methods and algorithms have been proposed to reduce the total number of evaluations required by EAs. Adaptive Range Genetic Algorithms (ARGAs), which were originally proposed by Arakawa and Hagiwara, are a unique approach to solve optimisation problems efficiently. The range adaptation was introduced to search optimal solution efficiently. Oyama developed real-coded ARGAs and applied them to the problem of transonic wing optimisation. ARMOGAs have been developed based on real-coded ARGAs to deal with multiple Pareto solutions for multi-objective optimisation.

Present ARMOGAs have been developed to consider the following things: sophisticated encoding system for multiple solutions, archiving technique, and constraint-handling technique. The encoding system is based on the normal distribution with the plateau region as shown in Fig.1, which are determined based on the population statistics to better preserve the diversity of solution candidates. Archiving and constraint-handling techniques are used to select better solutions that determine the new search range. A flowchart of ARMOGAs is shown in Fig. 2. The range adaptation starts at M_{sa} generation and is carried out every M_{ra} generations. The new decision space is determined based on the statistics of selected better solutions, and then the new population is generated in the new decision space. Thereafter, all the genetic operators are applied to the new design space.

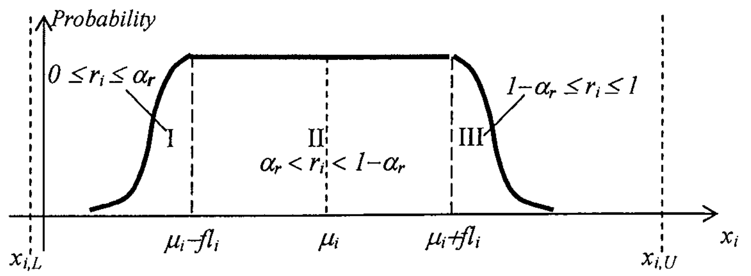


Fig. 1 Sketch of probability distribution of design variable xi in ARMOGAs.

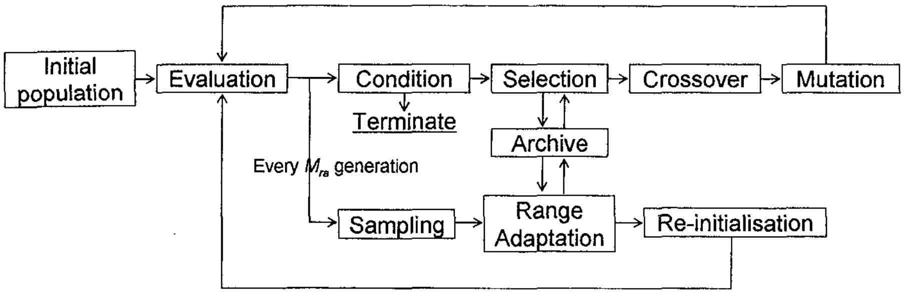


Fig. 2 Flowchart of ARMOGAs.

ARMOGAs were evaluated by applying them to five different types of Multi-Objective analytical problems. ARMOGAs showed reasonable search performance in all cases. ARMOGAs were also compared with another MOEA and two gradient-based methods: NSGA2 (Non-dominated Sorting Genetic Algorithms 2), SQP (Sequential Quadratic Programming method) and DHC (Dynamic Hill Climber method). ARMOGAs were able to find a reasonable quality non-dominated front with a small number of function evaluations comparable to DHC. On the other hand, gradient-based methods were not suitable for obtaining trade-offs, although DHC was slightly more robust than SQP. NSGA2 showed the similar search performance of ARMOGAs for unconstrained test problems. However, NSGA2 could not find well-dispersed non-dominated solutions of a constrained test problem. Therefore, ARMOGAs will be useful for multi-objective aerodynamic optimisation.

Chapter 3 Practical Multi-Objective Optimisation of LPC System

The capability of ARMOGAs has been discussed by demonstrating industrial multi-objective aerodynamic optimisation problems. The LPC system in modern aircraft gas-turbine engine with a high bypass ratio is considered as an optimisation problem. As the flow field around the cascade in the compressor is very complicated, Navier-Stokes (NS) solver has to be used to predict the flow field accurately. Two optimisations of OGV-Pylon-Bypass Duct system having 52 OGVs are demonstrated based on ARMOGAs coupled with in-house 2-D NS solver: Single-height and multi-height optimisations. The latter is considered to be a more practical problem, which has six design objectives considering three different heights.

Approximately 500 CFD evaluations were conducted and 11 non-dominated solutions were obtained in single-height optimisation. The non-dominated front represents the trade-off between the pressure variation at the inlet boundary and mixed-out total pressure loss.

Multi-height optimisation was then performed to consider more practical problems. Six-objective optimisation problem was efficiently solved by ARMOGAs and 32 non-dominated solutions were obtained in six objective-function space by nearly 750 CFD runs. Multiple trade-off analysis was conducted to understand the high-dimensional trade-offs. Trade-off analysis reveals that it is easy to reduce the pressure variation while maintaining the loss at 10 and 50%, and it is difficult to do that at 90% by just changing the re-stagger angles. The trade-off information, which can not be clarified by the conventional optimisation using utility function, is useful to improve the design.

Chapter 4 Multi-Objective Optimisation of SST Wing-Fuselage Configuration

To develop a next generation SST, significant research has been conducted. However, the next generation SST still has many technical obstacles to overcome. One of them is high aerodynamic efficiency for an economic flight, and another is low sonic boom for an environmental issue. These demands have a trade-off, because the reduction of sonic boom often leads to the increase of drag. To satisfy these demands, Multi-Objective optimisation has been performed in the present optimisation by using MOEAs.

The present optimisation is based on NAL's assignment at the SST design contest held in 2001. The design objective is to improve *L/D* at Mach number of 2.0, and to reduce the sonic boom at Mach number of 1.6. To create novel wing-fuselage configurations, wing and fuselage are simultaneously optimized. The geometry is defined by a total of 131 design variables. Based on these design variables, 3-D multiblock meshes were automatically generated around SST wing-fuselage configuration by Lawson's search and TFI method. Euler solver is used to evaluate aerodynamic performance. Darden's low-boom distribution of the equivalent area distribution is considered as the target to realise low-boom design.

Two optimisations (Case I and II) were performed to design low-drag, low-boom SST. As a result of both optimisation as shown in Fig. 3, trade-offs between drag and boom were obtained. The design of lowest boom has a thick fuselage to match Darden's distribution. On the other hand, the design of lowest drag design can not obtain good L/D due to the severe constraints.

Although the resulting optimal solutions in both cases have a variety of fuselage configurations, their wing shapes have a similar planform. Because a similar wing planform leads to a similar lift distribution, the fore fuselage has to thicken to match Darden's distribution for low boom. Thus, the low boom optimisation simply resulted in a thick fuselage with poor aerodynamic performance. The present result suggests that a lifting surface should be distributed innovatively to reduce both boom and drag, which will result in unconventional wing-fuselage configurations.

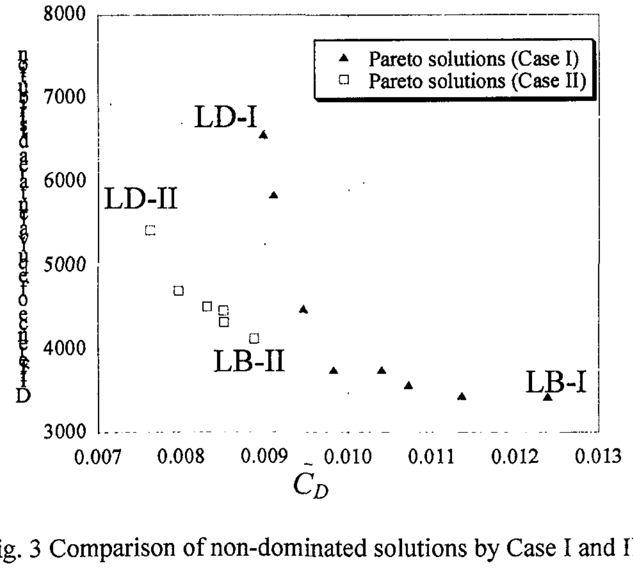


Fig. 3 Comparison of non-dominated solutions by Case I and II.

Chapter 5 Multi-Objective Optimisation of SST Canard-Wing-Fuselage Configuration

Advanced multi-objective aerodynamic optimisation system has been developed based on ARMOGAs to design SST wing-fuselage configurations equipped with canard. The canard is equipped with the hope to realise Darden's low-boom equivalent area distribution without an increase in drag. The effect of canard has been also discussed.

An automated design optimisation system of SST wing-fuselage in Chapter 4 is further developed to deal with a complex geometry. Unstructured mesh system is adapted for this system because of the flexibility. The wing and canard has a wide variety of planform shapes to represent unconventional configurations. The fuselage is determined by the area rule to promote the reduction of drag. The current SST is defined in total of 94 design variables. Unstructured mesh is automatically generated around SST canard-wing-fuselage configuration, and Euler solver is used to evaluate aerodynamic performances. Equivalent area distribution is also used to evaluate the low-boom configuration. The system utilised ARMOGAs and Master-Slave type parallelisation for each Euler computation to reduce the large computational burden. Two optimisations were conducted: one used eight individuals per generation and three PE PC clusters were used (Case I), while the other had 36 individuals per generation and the optimisations were conducted on SGI ORIGIN2000 parallel machines (Case II).

As a result of each optimisation, several non-dominated solutions that formed the trade-off between drag and boom were obtained. Figure 4 shows the optimisation history of Case I. The equivalent area distributions of two low-boom designs were quite similar to Darden's low-boom distribution by means of the canard and the swept back wing. Figure 5 shows a low-boom design of Case II. As the low-boom configuration could achieve *L/D* of 13, further improvements of such low-boom designs in terms of *L/D* may realise low-drag, low-boom SST. The SST equipped with canard can be a good candidate to realise SST.

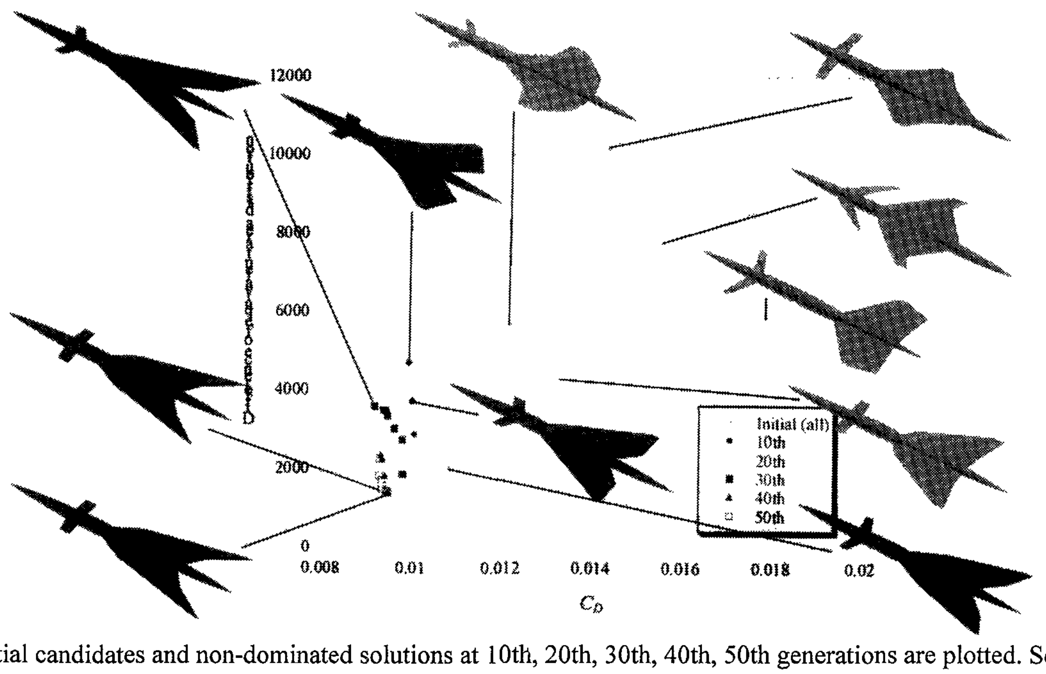
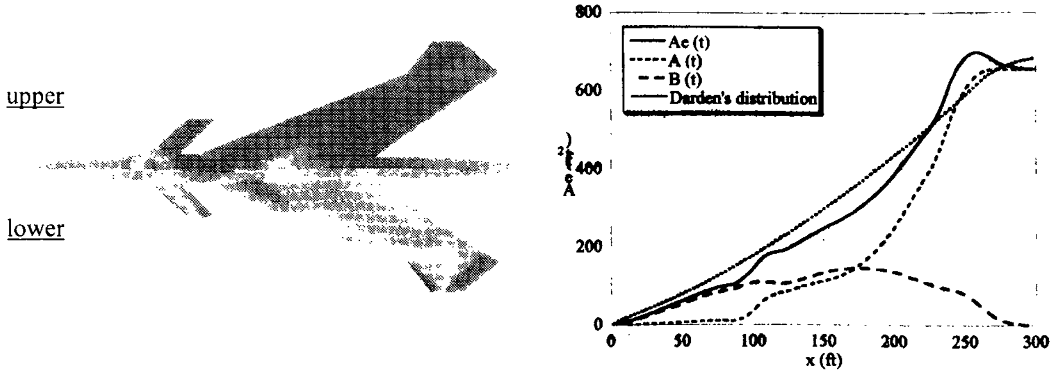


Fig. 4 Initial candidates and non-dominated solutions at 10th, 20th, 30th, 40th, 50th generations are plotted. Several corresponding configurations are also shown.



(a) Planform shape with pressure distributions (b) Equivalent area distributions of design and low-boom

Fig. 5 Configuration and result of a low-boom configuration.

Chapter 6 Conclusions

The objective of the study described in this thesis was to develop practical multi-objective aerodynamic optimisation systems based on MOEAs coupled with a high-fidelity CFD. For this purpose, ARMOGAs were developed and evaluated via analytical test problems and aerodynamic optimisation of industrial problems. ARMOGAs showed efficient search performance for such problems.

The MOEAs were actually applied to aerodynamic design problems to identify the trade-offs between multiple objectives. Multi-objective aerodynamic design optimisation systems of a next-generation SST were developed based on MOEAs to realise both low drag and low boom. Trade-offs between drag and boom were obtained with a small number of Euler computations based on these system. As a result of optimisation, a viable canard-wing-fuselage configuration was developed as compared to the wing-fuselage configuration.

論文審査の結果の要旨

数値流体力学（CFD）の進展と計算機性能の向上に伴い、航空機設計分野における空力最適化の重要性が増している。実際の設計問題では相反する設計要求が複数存在することが一般的であるため、多目的空力最適化を行い、トレードオフを得ることが必要である。精度良く空力計算を行うためには計算時間が非常に多くなることが一般的であるため、多目的空力最適化を効率的に解く手法の開発が産業界から求められてきた。そこで本論文では、効率的な多目的最適化手法として領域適応型多目的遺伝的アルゴリズム（ARMOGA）を提案し、それを実際の空力最適化問題に適用してその有効性を実証した。本論文は、この研究成果についてまとめたもので、全文６章よりなる。

第１章は緒論であり、本研究の背景及び目的を述べている。

第２章では、多目的進化アルゴリズムとして、探査空間を変化させることによって効率的に設計変数空間の探査を行うARMOGAを提案し、複数の数学的テスト関数に適用してその有効性の検証を行っている。他の最適化手法と比較して、少ない評価回数で目的関数間の実用的なトレードオフを得られることは、ARMOGAの有効性を示す重要な成果である。

第３章では、現実の工学的多目的最適化問題に対する有効性を評価するため、低圧圧縮機システムの空力最適化問題に対してARMOGAを適用している。ARMOGAは非常に少ないCFD計算回数で、それらの目的関数間に存在するトレードオフを明らかにすることに成功した。この結果は、企業にとってARMOGAが非常に魅力的な手法であることを示している。

第４章では、多目的進化的アルゴリズムに基づく超音速旅客機の多目的空力設計システムを構築し、最適化を行っている。３次元主翼と非軸対称胴体から成る翼胴形態を最適化対象とし、超音速旅客機実現のために必要不可欠である、空力抵抗とソニックブームの低減を図った。空力評価を自動的に行うシステムを構築するためマルチブロック格子を用い、Euler計算によって評価を行った。最適化の結果、抵抗とブーム間におけるトレードオフが明らかとなり、従来型の翼胴形態では低抵抗と低ブームを両立させることは不可能であることを示した。このことは、多目的空力最適化を行ってトレードオフを得ることの重要性を示す例として、重要な成果である。

第５章では、低抵抗と低ブームを両立させる超音速旅客機を実現するために、カナードを取り付けた翼胴形態を提案し、その形態の有効性を議論するために多目的空力最適化を行っている。最適化システムは、複雑な形状に対して格子を自動生成することのできる非構造格子Euler法と効率的な探査を行うARMOGAから成立している。最適化の結果、効率的に抵抗とブームに関するトレードオフを得ることに成功し、カナードと主翼のスイープにより低抵抗でかつ低ブームを実現する可能性があることを示したことは、非常に有用な成果である。

第６章は結論である。

以上要するに本論文は、効率的な多目的空力最適化システムの構築を行い、その有効性を実証したもので、流体科学ならびに情報科学の発展に寄与するところが少なくない。

よって、本論文は博士（情報科学）の学位論文として合格と認める。